DESIGN AND PERFORMANCE OF THE Z MAGNETICALLY-INSULATED TRANSMISSION LINES

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ABSTRACT

We have designed and tested a 10-nH 1.5-m-radius vacuum section for the Z accelerator. The vacuum section consists of four vacuum flares, four conical 1.3-m-radius magnetically-insulated transmission lines, a 7.6-cm-radius 12-post double-post-hole convolute which connects the four outer MITLs in parallel, and a 5-cm-long inner MITL which connects the output of the convolute to a z-pinch load. IVORY and ELECTRO calculations were performed to minimize the inductance of the vacuum flares with the constraint that there be no significant electron emission from the insulator-stack grading rings. Iterative TLCODE calculations were performed to minimize the inductance of the outer MITLs with the constraint that the MITL electron-flow-current fraction be $\leq 7\%$ at peak current. The TLCODE simulations assume a 2.5 cm/μs MITL-cathode-plasma expansion velocity. The design limits the electron dose to the outer-MITL anodes to 50 J/g to prevent the formation of an anode plasma. The TLCODE results were confirmed by SCREAMER, TRIFL, TWOQUICK, IVORY, and LASNEX simulations. For the TLCODE, SCREAMER, and TRIFL calculations, we assume that after magnetic insulation is established, the electron-flow current launched in the outer MITLs is lost at the convolute. This assumption has been validated by 3-D QUICKSILVER simulations for load impedances ≤ 0.36 ohms. LASNEX calculations suggest that the ohmic resistance of the pinch and conduction-current-induced energy loss to the MITL electrodes can be neglected in Z-power-flow modeling that is accurate to first order. To date, the Z vacuum section has been tested on 100 shots. We have demonstrated we can deliver a 100-ns rise-time 20-MA current pulse to the baseline z-pinch load. We have produced a 1.9-MJ x-ray yield; the project goal was 1.5 MJ. We can reproduce the peak MITL current to within $\pm 1.6\%$. Power-flow measurements indicate the vacuum section performs as expected until peak current. Afterward, measurements and simulation results diverge. TLCODE calculations indicate elimination of this discrepancy may increase by 20% the kinetic energy delivered to the pinch.

I. INTRODUCTION

The 36-module Z accelerator[1] was designed to drive z-pinch loads for weapon-physics and inertial-confinement-fusion experiments, and to serve as a testing facility for pulsed-power research required to develop higher-current (30-80 MA) drivers. The Z design builds upon experience gained from experiments performed on the Proto-II[2] and

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14. ABSTRACT

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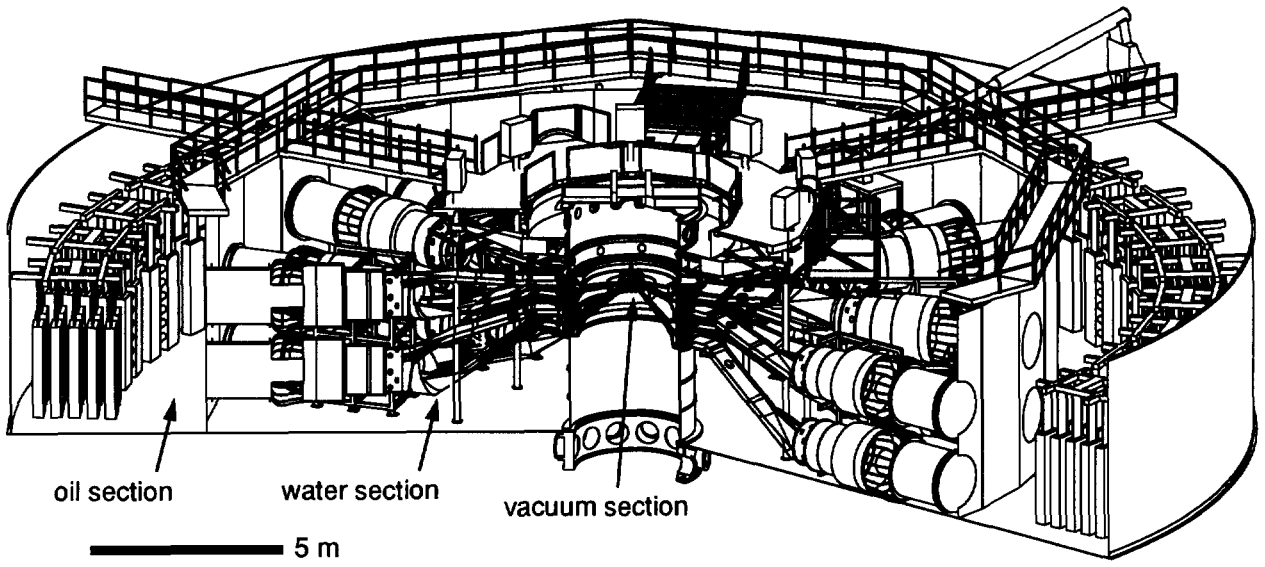


Figure 1. The Z accelerator.

Saturn[3] accelerators, which deliver 5 and 8 MA to z-pinch loads, respectively.

Z is contained in a 33-m-diameter tank with oil, water,[4,5] and vacuum[6-11] sections as shown in Figure 1. The peak total forward-going power in the 36 water-section bi-plate transmission lines is approximately 63 TW.[4,12] Nine transmission lines deliver power to each of the four vacuum-section levels.

In Sec. II.A we present an overview of the 10-nH vacuum-section design. We minimized the inductance of the vacuum-section flares and outer MITLs as described in Sec.'s II.B and II.C. The optimization of the convolute and inner-MITL designs is in progress; preliminary results are reported in Sec. II.D. Vacuum-gap closure is discussed in Sec. III. Sec. IV summarizes experimental and simulation results.

II. VACUUM-SECTION DESIGN

A. Overview. The water flares, insulator stack, vacuum flares, outer MITLs, double-post-hole convolute,[13] inner MITL, and z-pinch load are outlined in Figure 2. (The outer MITLs extend from the vacuum flares to the convolute; the inner MITL from the convolute to the load.) The four vacuum-section levels are labeled A, B, C, and D as shown. The nominal impedances of the axisymmetric outer MILTs at large radii are 2.1, 2.1, 2.7, and 2.7 ohms for levels A, B, C, and D, respectively. At a 10-cm radius, each MITL has a 1-cm anode-cathode gap.

The total inductance inside the stack-vacuum interface, not including the z-pinch load, is 8.52 nH. The vacuum-flare, outer-MITL, convolute, and inner-MITL inductances are 2.31, 2.93, 1.33, and 1.95 nH, respectively. The initial inductance of a 40-mm-diameter 2-cm-tall z-pinch with a 5-mm-radial anode-cathode gap and nine 9-mm-wide 2-cm-tall diagnostic slots in the return-current path is 1.1 nH.

B. Design of the vacuum flares. IVORY[14] and ELECTRO[15] simulations of the water-stack-vacuum interface were performed to optimize the design of the vacuum flares. The fully electromagnetic 2-D IVORY particle-in-cell (PIC) simulations show that electron emission from the stack grading rings can change the grading by as much as 50%.[8] For this reason, we minimized the inductance of the flares with the constraint that there be no significant emission from the rings. The rings were fabricated from aluminum and subsequently anodized to inhibit emission for fields below 300 kV/cm.[16] The electrostatic 2-D ELECTRO calculations were conducted at higher spatial resolution than the IVORY simulations, and were used to shape the flares to limit the fields at the rings to below this level.[10]

C. Design of the outer MITLs. TLCODE[17] circuit simulations of the four-level vacuum system were conducted to optimize the design of the outer MITLs.[6] Two z-pinch loads were assumed for the calculations: a 40-mm-initial-diameter 15-mg load (the baseline design for weapon-simulation experiments), and a 19-mm-initial-diameter 10-mg

load (for ICF research). Using the more inductive 19-mm load, we developed three outer-MITL designs: the 5-3.5-5, 10-7-10, and 20-14-20 configurations. To develop the 5-3.5-5 design, iterative TLCODE simulations were performed to find the outer-MITL impedance profiles that minimize inductance with the constraint that the electron-flow-current fraction be ≤ 5% at 2/3 of peak MITL current on the rising edge, ≤ 3.5% at peak current, and ≤ 5% 5 ns before the pinch implodes to 1/10 of its initial radius. The other two designs were developed accordingly.

Electron-flow current is estimated in TLCODE with Mendel's 1-D steady-state MITL equation[18] modified to account for cathode-plasma motion:

$$V = Z_o[1 - (vt/g)](I_a^2 - I_c^2)^{1/2} - (mc^2/2e)[(I_a^2 - I_c^2)/I_c^2].$$

In the above, V is the voltage, Z_o is the vacuum impedance, I_a is the anode current, I_c is the cathode current, g is the vacuum gap, v is the cathode-plasma-expansion velocity, and t is time since the plasma was formed. The vacuum impedance Z_o is known for each of the transmission-line circuit elements that constitute a MITL in a TLCODE simulation. At each time step we assume that V and I_a at each element are given by the TLCODE-calculated voltage and current. If the MITL element is insulated, we solve for I_c and the electron-flow current. For each outer MITL we set the flow current equal to the maximum value calculated for the MITL's elements; i. e., we assume once electrons are launched they do not convert downstream to cathode current. The calculations are valid when the flow-current fraction is small and the total transit time in the MITLs is short compared to the duration of the power pulse. Because we estimate that the skin depth of the cathode plasma is greater than its thickness, we make the simplifying assumption that the expansion of the cathode plasma affects only the flow current and does not change the inductance of the transmission-line elements.

The simulations assume the flow current launched in the outer MITLs is lost to the anode at the convolute. This

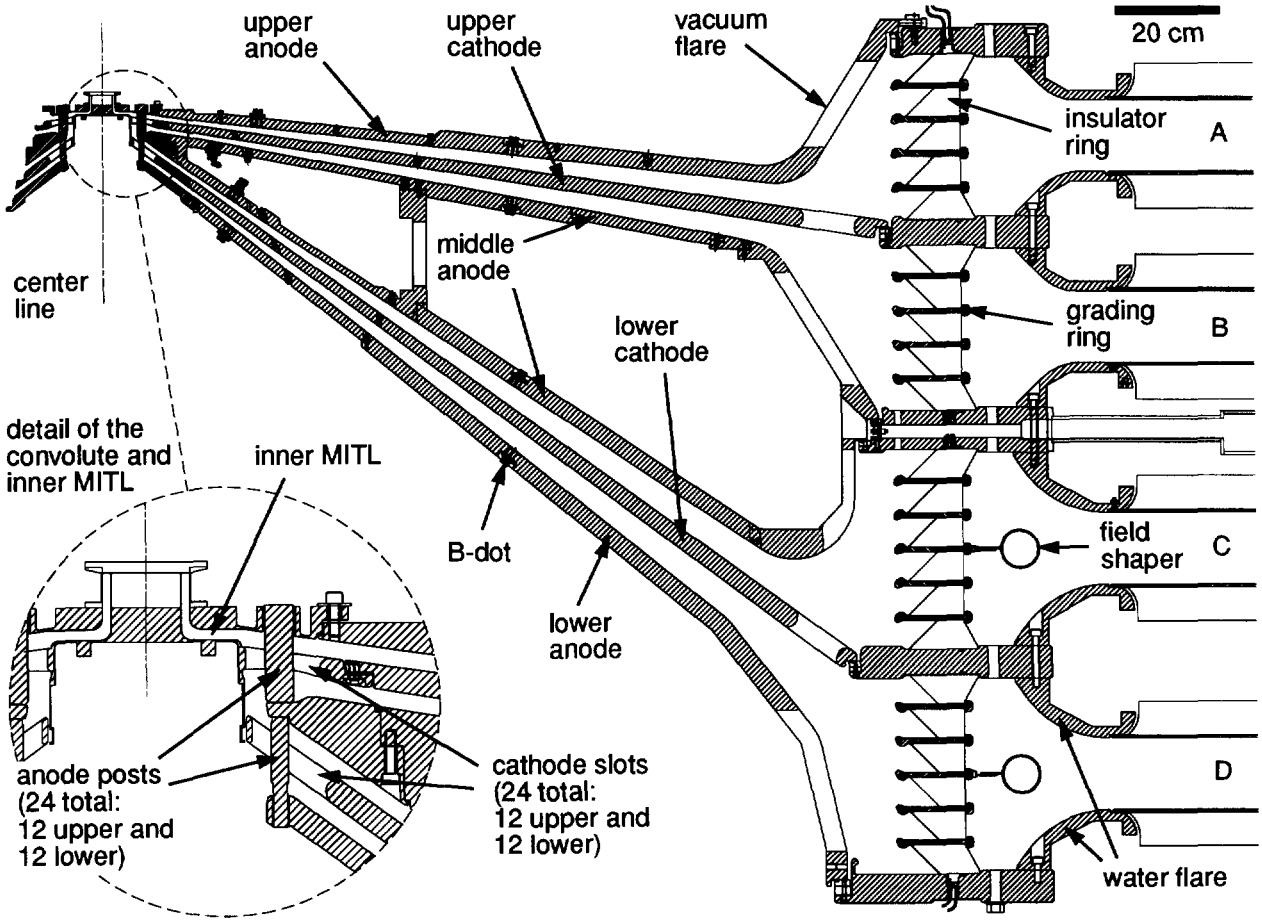


Figure 2. The Z vacuum section.

assumption is consistent with Saturn power-flow measurements, and has been validated by 3-D QUICKSILVER[19] simulations when the z-pinch-load impedance is ≤ 0.36 ohms.[9]

The TLCODE simulations show that the 10-7-10 design (outlined in Figure 2) optimizes system performance. With the 19-mm load, the three MITL designs deliver the same load current - and pinch kinetic energy - to within ±1%. The difference in inductance between the designs is offset by the difference in electron-flow current. With the baseline 40-mm load, the 5-3.5-5, 10-7-10, and 20-14-20 designs deliver 21.0, 21.6, and 22.2 MA load currents, respectively. The 5-3.5-5 option does not deliver 20 MA - the design goal - to the 40-mm load with sufficient margin for error (estimated to be 5%). The 20-14-20 design delivers more current to the 40-mm load than the 10-7-10 option, but also delivers twice the flow current, which would have doubled the costs of replacing and repairing hardware damaged by the deposition of flow electrons at the convolute. (On Saturn, the energy deposited at the convolute by the 0.6-1.2 MA flow current limits the lifetime of the convolute hardware to ~20 shots.)

The TLCODE simulations were validated by SCREAMER,[4,20] TRIFL,[21] TWOQUICK,[22] IVORY[8,14] and LASNEX[23] calculations. The currents predicted by the codes agree with each other to within ±2%. The codes explore different aspects of the design: TLCODE and SCREAMER use transmission-line and lumped-circuit elements to model the four-level vacuum section; TRIFL models - with expanded telegrapher equations for the anode, cathode, and flow currents - the Z vacuum section as a single-level 1-D MITL; TWOQUICK and IVORY provide 2-D PIC simulations of a single MITL; and LASNEX assumes the Z accelerator can be represented as an LR circuit (where R is the impedance of the 36 parallel water-section bi-plate transmission lines and L is the inductance of the water flares, stack, and vacuum section).

The LASNEX simulations model the z pinch as a 1-D MHD plasma. The other codes assume a zero-resistance imploding thin-walled cylinder. LASNEX predicts the pinch resistance (for 40-mm-diameter 2-cm-tall 15-mg aluminum and 19-mm-diameter 2-cm-tall 10-mg tungsten loads) is less than 10 milliohms during most of the implosion. (It is considerably higher for a few ns after t=0, and when the pinch has imploded to less than 1/10 of its initial radius.) Consequently, the resistance can be neglected in Z-power-flow calculations that are accurate to first order.

D. Design of the convolute and inner MITL. The double-post-hole-convolute and inner-MITL designs (Figure 2) were developed empirically on Proto-II and Saturn and have not yet been fully optimized. Saturn experiments with 6-, 10-, and 12-post convolutes and an argon-gas-puff z-pinch load resulted in 29, 32, and 34 kJ argon K-shell yields, respectively; as a result, the 12-post design was selected for Z.

Definitive modeling of the inherently 3-D convolute-inner MITL system requires 3-D PIC simulations. Time steps on the order of 10^{-14} s are needed to resolve the electron-cyclotron frequency for a 20-MA current at a 2-cm radius. Since it is not yet practical to track the entire power pulse (which would require ~10^7 time steps), simulations are being conducted that model the convolute-inner MITL system at a single point in time.

3-D QUICKSILVER PIC simulations (in Cartesian coordinates) of a 10-post single-post-hole convolute have been performed to model - at peak current - the operation of the Saturn convolute with a wire-array z-pinch load.[9] These show that electrons launched in the MITLs upstream of the convolute are lost to the anode in the convolute region, but that the intrinsic convolute efficiency is, to within the numerical accuracy of the computations, 100%. The calculations assume the convolute current and load impedance are 7 MA and 0.36 ohms, respectively. 3-D LSP[24] PIC simulations (in cylindrical coordinates) of the Z 12-post double-post-hole convolute were performed at $I_{convolute}$ = 20 MA and Z_{load} = 0.115 ohms (peak-current parameters for a typical Z shot), and also predict that the intrinsic convolute efficiency is nearly 100% for low-impedance loads. Additional simulations will explore the consequences of electron deposition in the convolute region, such as anode-plasma formation and subsequent gap closure, and will be used to minimize the inductance of the convolute and inner MITL with the constraint that the anode-cathode gaps remain open during the power pulse.

Preliminary LASNEX calculations suggest that energy lost to the inner-MITL electrodes due to the conduction current can be neglected in Z-power-flow calculations. The current in the simulations (which assume copper electrodes) increases linearly from 0 to peak in 100 ns, and remains constant afterward for an additional 20 ns. The simulations predict that the total time-integrated energy lost to the electrodes for peak lineal current densities of 1.4, 2.9, 7.2, and 14.5 MA/cm is 4.2×10^1, 4.2×10^2, 7.2×10^3, and 5.8×10^4 J/(cm^2 of electrode area), respectively.

III. ANODE-CATHODE GAP CLOSURE

Measured values of the cathode-plasma-expansion velocity typically range from 1 to 2.8 cm/μs.[25-28] For the TLCODE simulations we arbitrarily assume 2.5 cm/μs.

The simulations assume no anode plasma is formed. According to TWOQUICK and IVORY calculations, the peak electron dose to the outer-MITL stainless-steel anodes is 50 J/g, which increases the anode-surface temperature to 120 °C. Electron-beam-diode experiments suggest 400 ± 60 °C is required for anode-plasma formation.[29]

Because the electron dose to the anodes is low, the electrostatic-gap-closure relation[30] is not applicable to the design of the outer MITLs. The relation is consistent with 1-D NEUTRAL PIC simulations;[31] however, these assume the anode is a space-charge-limited source of ions.

Electrostatic gap closure may play a role in the performance of the convolute and inner MITL. 3-D QUICKSILVER simulations show that electrons launched in the outer MITLs are lost to the anode at the convolute. The electron deposition at the convolute's magnetic nulls is sufficient to vaporize macroscopic quantities of stainless steel on a single shot. Optimized convolute and inner-MITL designs would minimize the inductance with the constraint that the anode-cathode gaps not close on the time scale of the pulse. The development of optimized designs (with 3-D PIC simulations, electrostatic-gap-closure calculations, and experiments on Z) is in progress.

IV. RESULTS

To date, the Z vacuum section has been tested on 100 shots. On shot 51 the x-ray yield was 1.9 MJ. (The project goal was 1.5 MJ). The shot was taken with a 40-mm-diameter 2-cm-tall 4.1-mg tungsten-wire-array load.[1]

The peak MITL currents on shots 51 and 52 (nominally identical except for the x-ray diagnostic configuration) differ by 0.5%. Measurements made on ten nominally-identical shots with a 30-mm-diameter 2-cm-tall 5.4-mg wire-array load indicate the current can be reproduced to within ±1.6%.

For shots 51 and 52, the TLCODE-calculated values for the stack power, stack energy, stack voltage for levels A, B, C, and D, total MITL current, and implosion time are 53.6 TW, 3.45 MJ, 2.97 MV, 2.99 MV, 3.45 MV, 3.53 MV, 20.1 MA, and 102 ns, respectively. The average measured values[32] for the two shots are 52.6 TW, 3.22 MJ, 2.90 MV, 3.20 MV, 3.37 MV, 3.50 MV, 20.3 MA, and 104 ns. The agreement is acceptable given the simplifying assumptions in the calculations.

It appears, however, that measured and simulated MITL currents diverge after peak current, as shown in Figure 3. Measured and calculated stack voltages also diverge, except unlike the MITL currents, the measured voltages fall below the simulation results. The voltage and current measurements can be replicated in TLCODE with the addition of a shunt resistor at the convolute that drops in resistance from 4.5 ohms at peak current to 0.3 ohms when the pinch reaches 1/10 of its initial radius. According to the simulations, elimination of the late-time drop in impedance would increase by 20% the kinetic energy delivered to the pinch. Experiments and calculations designed to resolve the discrepancy are in progress.

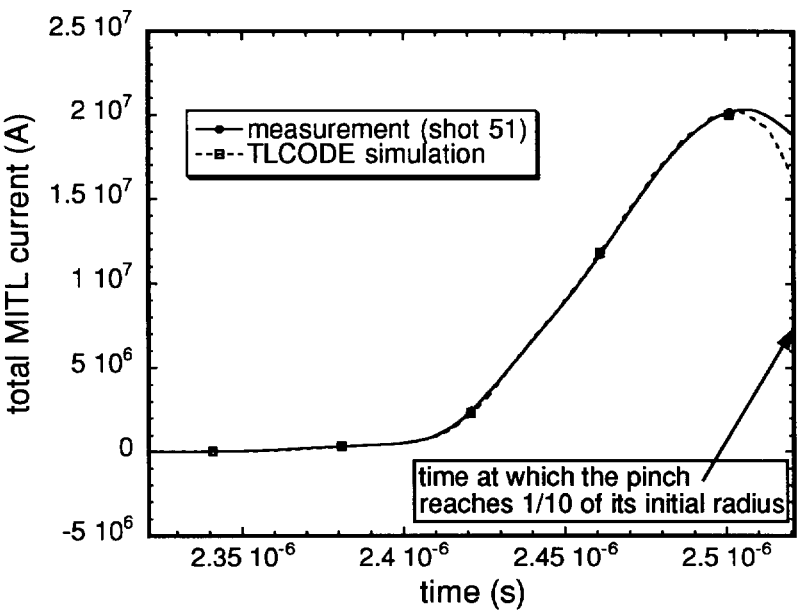


Figure 3. Measured and simulated MITL currents for Z-shot 51.

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[1]R. B. Spielman et. al., these proceedings.
[2]R. B. Spielman, D. L. Hanson, M. A. Palmer, M. K. Matzen, T. W. Hussey, and J. M. Peek, J. Appl. Phys. **57**, 830 (1985).
[3]R. B. Spielman et. al., in *Dense Z Pinches*, edited by N. R. Pereira, J. Davis, and N. Rostoker, AIP Conf. Proc. #195 (AIP, New York, 1989), p. 3.
[4]K. W. Struve, T. H. Martin et. al., these proceedings.
[5]R. J. Garcia et. al., these proceedings.
[6]P. A. Corcoran et. al., these proceedings.
[7]H. C. Ives, D. M. Van De Valde et. al., these proceedings.
[8]Michael. A. Mostrom et. al., these proceedings.
[9]D. B. Seidel and C. W. Mendel, Jr., these proceedings.
[10]R. W. Shoup et. al., these proceedings.
[11]I. D. Smith et. al., these proceedings.
[12]K. W. Struve, M. L. Horry et. al., these proceedings.
[13]R. B. Spielman, P. Corcoran, J. Fockler, H. Kishi, and P. W. Spence, in *Proc. of the 7th IEEE International Pulsed Power Conference* (1989), p. 445.
[14]M. M. Campbell, B. B. Godfrey, and D. J. Sullivan, Mission Research Corporation Report AMRC-R-454 (1988) (revised).
[15]Integrated Engineering Software, Winnipeg, Manitoba, Canada.
[16]G. B. Frazier, in *Proc. of the 2nd IEEE International Pulsed Power Conference* (1979), p. 127.
[17]W. N. Weseloh, in *Proc. of the 7th IEEE International Pulsed Power Conference* (1989), p. 989.
[18]C. W. Mendel, Jr., M. E. Savage, D. M. Zagar, W. W. Simpson, T. W. Grasser, and J. P. Quintenz, J. Appl. Phys. **71**, 3731 (1992).
[19]D. B. Seidel et. al., in *1991 Proc. of the CP90 Europhysics Conf. on Computational Physics*, edited by A. Tenner (World Scientific, Singapore), pp. 475-482, and J. P. Quintenz et. al., Laser and Particle Beams **12**, 283 (1994).
[20]M. L. Kiefer and M. M. Widner, in *Proc. of the 5th IEEE International Pulsed Power Conference* (1985), p. 685.
[21]L. P. Mix et. al., in *1996 IEEE International Conf. on Plasma Science Record - Abstracts* (New York, 1996), p. 129.
[22]T. D. Pointon, J. Comput. Phys. **96**, 143 (1991).
[23]G. B. Zimmerman and W. L. Kruer, Comments Plasma Phys. **2**, 51 (1975).
[24]Mission Research Corporation, Albuquerque, New Mexico, USA.
[25]R. K. Parker, Richard E. Anderson, and Charles V. Duncan, J. Appl. Phys. **45**, 2463 (1974).
[26]R. W. Stinnett, M. A. Palmer, R. B. Spielman, and R. Bengston, IEEE Trans. on Plasma Science **PS-11**, 216 (1983).
[27]G. A. Mesyats and D. I. Proskurovsky, Pulsed Electrical Discharges in Vacuum, (Springer-Verlag, New York, 1989).
[28]V. G. Kovalev, O. P. Pecherskii, Yu. M. Savel'ev, K. I. Tkachenko, V. I. Engel'ko, and M. Chulpek, Sov. Phys. Tech. Phys. **37**, 813 (1992).
[29]T. W. L. Sanford et. al., Sandia National Laboratories Report SAND88-1297 (1988).
[30]J. P. VanDevender, in *Proc. of the 3rd IEEE International Pulsed Power Conference* (1981), p. 248.
[31]T. D. Pointon, J. Appl Phys. **66**, 2879 (1989).
[32]W. A. Stygar, R. B. Spielman, H. C. Ives et. al., these proceedings.